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FERGUS TS - POWER FREQUENCY GROUNDING STUDIES

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Power frequency tests under simulated fault conditions were conducted at Fergus TS after the installation of a new ground grid between the station and the microwave area, in order to evaluate the adequacy of the grounding system performance at the station. The station ground potential rise (GPR) and touch and step potentials were measured. Soil resistivity tests were also performed near the station. Models were developed to generalize the results. For an ultimate HV fault current of 10 kA, the measured and modelled station ground potential rises were found to exceed the permissible limit of 5 kV. The fence touch voltage and the station mesh and step voltages for the above fault current of 10 kA are all well within the tolerable limits. The estimated GPR for an LV fault current of 5.5 kA approaches the permissible limit of 5 kV. Simplified calculations indicated that significant improvement in the station GPR could be obtained by bonding the under-built distribution neutrals to the station ground grid.

1.0 INTRODUCTION

Fergus TS is an existing 230-kV station supplying loads to farm houses. The station facilities include a microwave tower located about 150 m north-west of the station. Problems have been experienced at the station during thunder storms when lightning strikes in the vicinity of the microwave tower cause protective gap flashovers and equipment damage on control wiring between the microwave building and the station. The reason for the flashover was thought to be inadequate grounding or cable shielding. Therefore, a new ground grid has recently been installed between the station main ground grid and the microwave area in order to improve the grounding system performance at the station. A Series of tests was conducted at the station before and after the installation of the new grid in order to investigate and evaluate the transient performance of the ground grid. Also, power frequency tests under simulated fault conditions were conducted at the station after the installation of the new grid in order to confirm the adequacy of the grounding system performance with respect to public safety, station security and protection of telecommunication equipment.

This report covers the power frequency performance of the grounding system at Fergus TS. A separate report will cover the transient performance of the station grounding system. The project was requested and funded by Transmission Stations Programs Department.

job	file	date	report no.
18-240-433	813.521	August 18, 1989	89-192-K

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2.0 STATION FACILITIES

Fergus TS is tapped off from the 230-kV double circuits D6V and D7V between Detweiler TS and Orangeville TS. The station has two transformers rated 75 MVA, 215.5 kV/44 kV, Y/Y_{rg}, where rg means reactor-grounded. The station supplies loads through five 44-kV feeders. The ground grids at the station and the microwave tower area are interconnected through a recently installed ground mesh. Figure 1 shows the layout of the station with respect to the grounding system. The two 51 mm_2 (3/8") steel skywires of the HV circuits are connected to the main station grid. The 44-kV system has no neutrals on the feeders leaving the station. The under-built neutrals of the secondary distribution system in the area are tied back to the DS and are not connected to the station ground grid.

3.0 TEST PROCEDURE

Power frequency grounding tests were conducted at Fergus TS on April 11, 1989 and Figure 1 shows the layout of the station with respect to the tests. A test current of approximately 6 A at 240 V, 67 Hz from a diesel generator installed in a Research Division van was injected between the station ground and a remote temporary ground rod using a dedicated test lead. The following measurements were made:

(a) Station ground potential rise between a remotely grounded Bell telephone pair and local station ground.
(b) A potential profile north of the station.
(c) Mesh and step potentials at the station.
(d) Fence potentials at the station.
(e) Step potentials in the area between the station and the microwave tower.

One of the remotely grounded pairs of the Bell neutralizing transformer at the station was isolated from the primary winding for measurement in (a) above. The potentials (both magnitude and phase angle) were recorded with reference to 1.00/0 A injected test current using an HP3582A spectrum analyzer in conjunction with a differential amplifier. The analyzer is capable of differentiating the 67 Hz test signals from 60 Hz noise. The reference current was measured using a clamp-on current transformer with shunt.

Two soil resistivity surveys using the Wenner method /1/ were conducted near the station, one on March 30, 1988 in the field north of the station property and the other on April 12, 1989 along the road south of the station. A Megger DET-2 ground resistance tester was used to take the Wenner readings.

A separate test was also conducted to develop a new simple method to verify the continuity of buried ground grid conductors. The method is based on monitoring the magnetic fields produced by test currents flowing in the grid conductors. Here, a large test current of approximately 275 A at 240 V, 67 Hz was injected locally between two ground grid risers to structures. The test current was obtained from the van-mounted diesel generator using a variac, a special low-inductance transformer and a flexible cable. The current splits in the grid conductors were monitored using a portable conductor tracer which consists of a hand-held wand with an inductive pick-up coil and headphone set. The pick-up coil receives the magnetic field produced by the test current in the grid conductor. The output of the coil is amplified and an equivalent audio signal is heard via the headphones. Voltage drops between selected points on the grid conductors were also monitored using the spectrum analyzer and the current transformer described above. The findings should be useful for further development of the method and are not discussed in this report.

Safety precautions were observed during the tests in order to control and minimize any hazardous voltages that may appear in the event of a system fault.

4.0 MEASURED RESULTS

4.1 Measured Soil resistivity

Table 1 lists the apparent resistivities calculated from the measured Wenner data using equation 7.1 of the Grounding Guide /1/, along with the modelled values. Survey #1 was conducted in the swampy field north of the station and the weather on the test date was sunny. Survey #2 was conducted along the road south of the station property and the weather on the test date was cloudy and cold with light snow.

TABLE 1

FERGUS TS - SOIL RESISTIVITIES

Probe Spacing (m)	Apparent Resistivities (Ω.m)			
	Survey #1 (88-03-30)		Survey #2 (89-04-12)	
	Measured	Modelled	Measured	Modelled
1	73.9	130.0	157.1	80.0
2	104.6	130.0	127.2	80.0
5	144.5	145.0	78.9	84.0
10	209.9	210.0	98.8	100.0
20	349.4	350.0	156.5	156.0
50	700.6	660.0	302.5	302.0
100	908.6	910.0	-	-
Fitted Two-Layer Model Parameters				
	ρ_1 = 120 Ω.m		ρ_1 = 80 Ω.m	
	d = 7 m		d = 12.5 m	
	ρ_2 = 1200 Ω.m		ρ_2 = 800 Ω.m	

4.2 Measured Ground Potential Rise

The measured ground potential rises (GPR) at the station are given in Table 2, along with the modelled value. For an injected fault current of 10 kA (ultimate fault level), the maximum measured station ground potential rise is 9.1 kV.

The Bell remote pairs are routed towards west along the road south of the station and therefore, mutual coupling between the Bell pair and the current injection lead was neglected.

For the potential profile measurements, the current injection lead and the potential lead were approximately at right angles and mutual coupling between them was neglected. But the potential lead ran parallel to the skywires for the first 150 m and then at an angle of approximately 45° to the skywires for the remaining 100 m causing mutual coupling due to the skywire split. Also the current injection to remote current probe caused voltage rises at the remote potential probes due to conductive coupling. Simplified calculations were performed to estimate the correction factors to compensate for these effects and the net correction factor was found to be negligible. Therefore, the actual measured profile readings were plotted against inverse distance which were then extrapolated to infinite distance at the ordinate to give ground potential rise. This assumes uniform resistivity and point current injection /2/.

TABLE 2

FERGUS TS - GROUND POTENTIAL RISE (mV/A)

	Measured	Modelled
From Bell Pair	879.9/-1	572.3/2
From Potential Profile	910.0/1	572.3/2

4.3 Measured Touch and Step Voltages

Station touch and step voltages were measured at several locations and the worst cases are presented in Table 3, along with modelled results. A maximum voltage of 1.1/68 mV/A was measured between the station fence and the station ground grid.

TABLE 3

FERGUS TS - TOUCH AND STEP VOLTAGES (mV/A)

	Measured	Modelled
Fence Touch Voltage		
a) Outside	45.8/8	33.3/2
b) Inside	43.4/2	-
Station Mesh Voltage	9.4/12	24.6/2
Station Step Voltage	2.5/-11	10.9/2
Step Voltage Between Station and Microwave Building	2.4/3	-

5.0 TOLERABLE LIMITS OF TOUCH AND STEP VOLTAGES

The tolerable touch and step voltage limits were calculated using equations 2.4 and 2.2 of the Grounding Guide /1/. Assuming 80 mm of crushed stone layer at the station, the calculated touch and step voltage limits for the station are 575 V and 1857 V respectively. For general public standing on soil outside the station, the tolerable touch and step voltage limits were calculated as 188 V and 263 V respectively.

6.0 MODELLED RESULTS

Appendix A summarizes the formulas used in the calculations, other than those given in the references.

6.1 Soil Resistivity

The measured soil resistivity data was interpreted as a two-layer soil model using the method given in Appendix D of the Grounding Guide /1/. The resulting two-layer model parameters are given in Table 1. The two-layer models from surveys 1 and 2 yielded equivalent soil resistivities of 420 Ω.m and 248 Ω.m respectively, for an estimated station radius of 70 m. Based on the results, an

average equivalent resistivity of 330 Ω.m was used in calculating the station ground resistance and skywire impedances. An average sub-surface layer resistivity of 100 Ω.m was used in calculating touch and step voltages at the station.

6.2 Isolated Station Ground Resistance

The isolated station ground resistance R_g was calculated as 1.25 Ω using equation 3.1 of the Grounding Guide /1/, based on a total ground grid area of 15,916 m^2 and 3812 m of buried grid conductors. This includes the main station ground grid, the ground grid at the microwave area and the newly installed grid between the two (see Figure 1). An equivalent station radius of 70 m was calculated from the total grid area.

6.3 Skywire Impedance

For the two 51 mm_2 (3/8") steel skywires of the 230 kV double circuit line, the conductor earth return self impedance and the mutual impedance to phase conductors were calculated as $2.60\angle 35$ Ω/km and $0.37\angle 81$ Ω/km respectively, using simplified formulas for Carson's earth return impedances. Based on an estimated tower footing resistance of 8 Ω and a span length of 300 m, the conductive chain impedance Z_c of the skywire was calculated as $1.25\angle 17$ Ω.

6.4 Skywire Shielding Factor

For an HV station fault, only the conductive component of the fault current enters the station grounding system due to the shielding of the skywires. This conductive component of the fault current was calculated as SI_f where, S is the shielding factor calculated from the skywire self and mutual impedances. The inductive component of the skywire split is $(1-S)I_f$. The calculated shielding factor is $0.91\angle -7$.

6.5 Modelled Results for an HV Station Fault

Figure 2 shows the conductive equivalent circuit of the grounding system at the station. The distribution neutrals are not included in the model as they are not connected to the station ground grid. The interconnected station ground impedance was calculated as $0.63\angle 9$ Ω. The conductive equivalent circuit in Figure 2 was solved for an injected current of S x $1.00\angle 0$ A for an HV station fault and the calculated current splits are $0.46\angle 2$ A for the station ground and $0.54\angle -2$ A for the skywires. Here, the skywire split is the sum of the conductive and inductive components.

The station ground potential rise was calculated as $I_g R_g$ where I_g is the ground current split and R_g is the isolated station ground resistance and is given in Table 2, along with the measured results. For an ultimate HV fault current of 10 kA, the calculated station ground potential rise is approximately 5.7 kV.

The station mesh and step voltages and the fence touch voltage to the public outside were calculated using equations 70 and 73 of the IEEE Guide 80 /3/ and equation 3.10 of the Grounding Guide /1/, respectively. The calculated touch and step voltages are given in Table 3, along with the measured results. For an ultimate HV fault current of 10 kA, the modelled station mesh and step voltages and the fence outside touch voltage are approximately 246 V, 109 V and 333 V respectively.

6.6 Estimated Results for an LV Fault

An LV fault at the station will not cause any ground potential rise as the fault current circulates within the station without entering the station ground. Simplified calculations based on several assumptions (see Appendix B) were performed to estimate the station ground potential rise in the event of a 44-kV line-to-ground fault on a pole carrying under-built neutrals outside the station. Here, the total fault current would be limited by the source impedance, the earth return self

impedance of the faulted phase conductor and the chain impedance of the under-built neutral conductor. The estimated fault current is 5.5 kA.

There is no return current through the distribution feeder neutrals as they are not bonded to the station ground grid. Assuming that the entire fault current returns through the skywires and the station ground, the estimated station ground current split and the corresponding station ground potential rise would be 0.50/9 A and 630.0/9 mV/A respectively. For the estimated fault current of 5.5 kA, the station ground potential rise would be 3.5 kV.

7.0 DISCUSSION OF RESULTS

7.1 The soil resistivity surveys near the station indicate a multi-layer soil structure. The differences in the measured results from the two surveys (Table 1) may be due to the variations in the soil conditions at the two test locations especially during the different weather conditions on the two test dates (see section 4.1). An average equivalent soil resistivity of 330 Ω.m based on the results from the two surveys was considered adequate for estimating the station ground resistance.

7.2 With no bonding between the station ground grid and the secondary distribution neutrals, the fault currents entering the station grounding system split mainly between the station ground and the skywires. About 46% of the total fault current was found to enter the station ground, as modelled.

7.3 For an ultimate HV fault current of 10 kA, both the measured and the modelled station ground potential rises of 9.1 kV and 5.7 kV respectively, exceed the permissible limit of 5 kV.

7.4 The lower value of the station ground potential rise measured using the remotely grounded telephone pair compared to that from the potential profile data is probably caused by induction due to current splits in the adjacent loaded pairs in the cable. Since the difference in the two measured results is less than 4% and enough data was not readily available, no attempt was made to estimate a correction factor to compensate for this error.

7.5 The modelled station ground potential rise is approximately 37% lower than the maximum measured value. The estimated station ground resistance based on an equivalent station radius for the oblong grid geometry (Figure 1) and an average equivalent soil resistivity may not be conservative.

7.6 Simplified calculations based on several assumptions (see Appendix B) indicated that bonding between the under-built neutrals and the station grid could reduce the ground current split by about 37%. The corresponding station ground potential rise would be approximately 3.6 kV for an ultimate HV fault current of 10 kA and is well below the permissible limit of 5 kV.

7.7 For the above fault current of 10 kA, the measured and the modelled fence outside touch voltages of 458 V and 333 V respectively are both under the tolerable touch voltage limit of 575 V calculated for the station. The model may not be conservative as explained in section 7.5 above. The relatively low voltage of 1.1 mV/A (approximately 0.1% of the station ground potential rise) measured between the station fence and the station ground grid indicates that the station fence is bonded to the station ground grid as shown in the design drawings.

7.8 For the above fault current of 10 kA, the measured and the modelled mesh and step voltages are all well below the tolerable limits.

7.9 In the event of an LV fault on a pole outside the station, the calculated station ground potential rise of 3.5 kV for an estimated fault current of 5.5 kA is well below the permissible limit of 5 kV. Simplified calculations with bonding between the under-built distribution neutrals and the station grid indicated that the station ground potential rise for the above estimated LV fault current of 5.5 kA would be considerably reduced to approximately 2.2 kV which is well under the recommended limit of 3 kV. As these estimated results for an LV fault do not produce the worst case ground potential rise, a detailed study was not considered necessary at this time.

8.0 CONCLUSIONS

8.1 Soil resistivity measurements at Fergus TS indicated a multi-layer soil structure at the station. A two-layer interpretation of the test data from the two resistivity surveys near the station gave the following results.

Survey #1 : ρ_1 = 120 Ω.m, d = 7 m, ρ_2 = 1200 Ω.m

Survey #2 : ρ_1 = 80 Ω.m, d = 12.5 m, ρ_2 = 800 Ω.m

The differences in the results are probably due to the variations in the soil conditions at the two survey locations on the two different test dates.

For the station ground resistance calculation, an equivalent resistivity of 330 Ω.m was derived from the above two-layer models based on an estimated station radius of 70 m. An average sub-surface layer resistivity of 100 Ω.m was used in calculating the touch and step voltages.

8.2 The isolated station ground resistance estimated from the grid geometry is 1.25 Ω.

8.3 With no bonding between the station ground grid and the distribution neutrals, the fault current entering the station grounding system splits mainly between the skywires and the station ground. An interconnected station ground impedance of $0.63\underline{/9}$ Ω and a skywire shielding factor of $0.91\underline{/-7}$ were calculated for the station.

8.4 For an HV station fault, the modelled current splits are approximately 46% for the station ground and 54% for the skywires.

8.5 For an ultimate HV fault current of 10 kA, the maximum measured and the modelled station ground potential rises are approximately 9.1 kV and 5.7 kV respectively. Both the values exceed the permissible limit of 5 kV.

8.6 For the above fault current of 10 kA, the maximum measured and the modelled station fence outside touch voltages are 458 V and 333 V, respectively. Both are under the tolerable touch voltage limit of 575 V calculated for the station. Measurements indicated that the station fence is connected to the station ground grid as shown in the design drawings.

8.7 For the above fault current of 10 kA, the maximum measured and the modelled station mesh voltages of 94 V and 246 V respectively are both under the tolerable touch voltage limit of 575 V.

8.8 The maximum measured and the modelled station step voltages of 25 V and 109 V respectively for the above fault current of 10 kA are both well under the tolerable limit of 1857 V calculated for the station.

8.9 A maximum step voltage of approximately 24 V for the above fault current of 10 kA was measured in the area between the station and the microwave building which is accessible to the public (where the new grid has been installed). This voltage is well under the tolerable step voltage limit of 263 V calculated for general public standing on soil.

8.10 Simplified calculations indicated that an LV fault does not produce the worst case station ground potential rise. The estimated station ground potential rise in the event of an LV fault on a pole outside the station is approximately 3.5 kV for a fault current of 5.5 kA.

8.11 Simplified calculations indicated that significant reduction (of about 37%) in the station ground current split and the station ground potential rise could be obtained with bonding between the under-built distribution neutrals and the station ground grid. With the neutrals bonded to the station grid, the estimated station ground potential rises are 3.6 kV and 2.2 kV respectively for the above HV fault current of 10 kA and the LV fault current of 5.5 kA.

9.0 ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance and cooperation from District P&C, Central Region Telecommunication group and Station maintenance in conducting the tests and the study. Valuable discussions and contribution from Design and Development Division-Transmission, System Planning, Power System Operations Division and Central Region Distribution Systems are gratefully acknowledged.

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1. Ontario Hydro Guide for Grounding, 1982 Revision.

2. E.P. Dick, "Modeland TS - Grounding System Resistance and Soil Potential Profile", Ontario Hydro Research Division Report 82-325-K, February 28, 1983.

3. IEEE Standard 80, IEEE Guide for Safety in AC Substation Grounding, 1986 Revision.

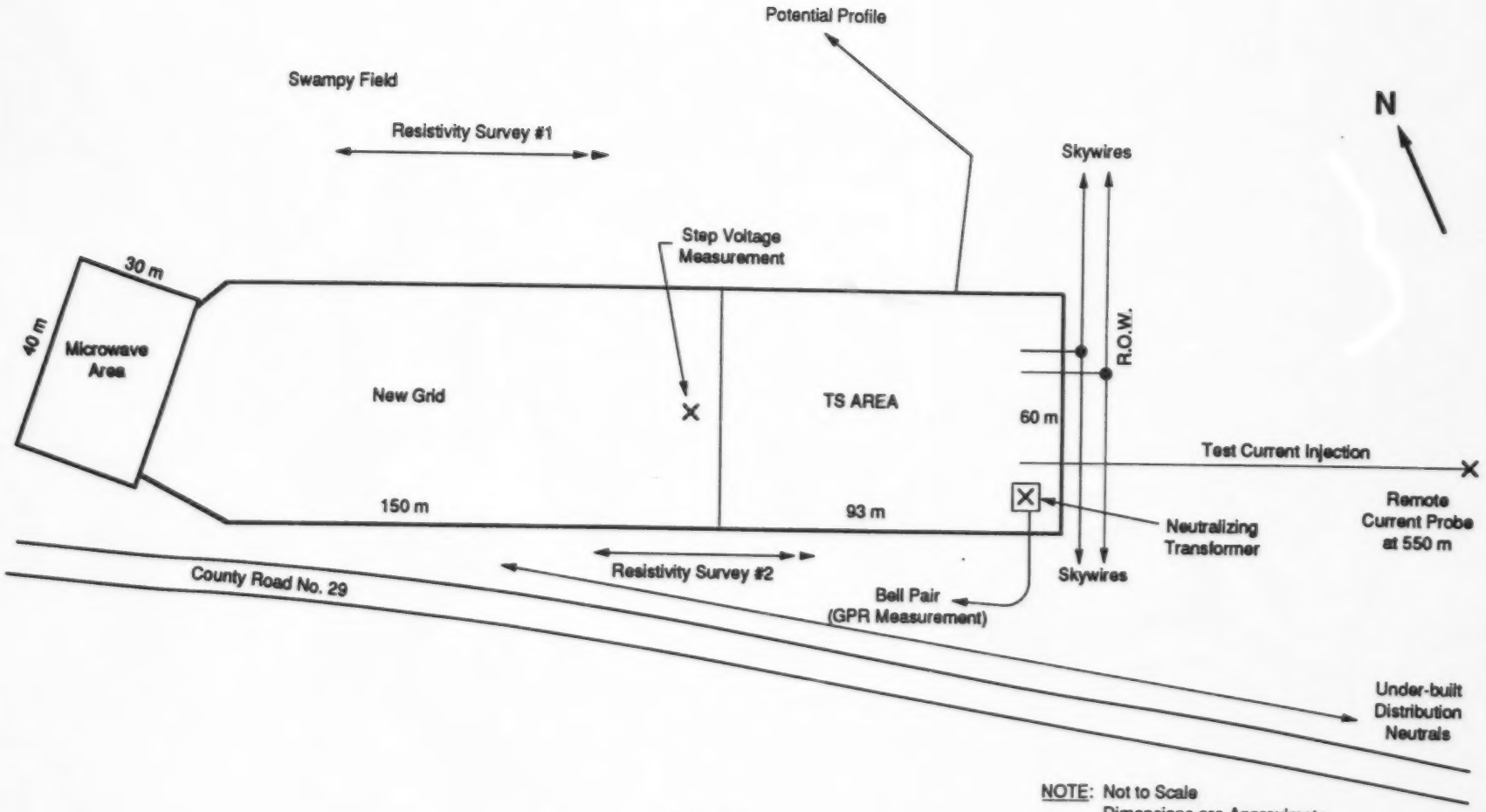

FIGURE 1

FERGUS TS
LAYOUT WITH RESPECT TO GROUNDING TESTS

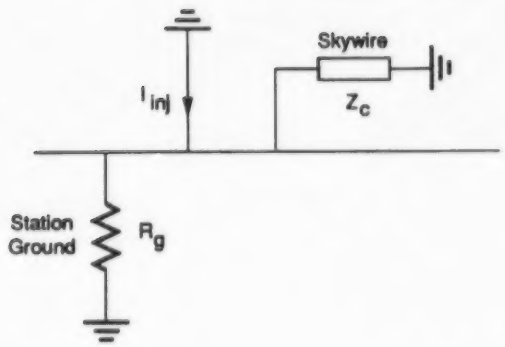

FIGURE 2

FERGUS TS
CONDUCTIVE EQUIVALENT CIRCUIT

APPENDIX A

SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/km) \qquad (1)$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/km) \qquad (2)$$

$$X_s = 0.0377 \ln (8440 \rho_s / GMR^2) \qquad (3)$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in Ontario Hydro Research report No. 83-433-K, dated November 7, 1983, by E.P. Dick.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/km) \qquad (4)$$

$$R_m = 0.0377 \tan^{-1} (8440 \rho_s / GMD^2) \qquad (5)$$

$$X_m = 0.0377 \ln [(8440 \rho_s / GMD^2) + 1] \quad (\Omega/km) \qquad (6)$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean diastance between conductors (m)

3. Tower Footing Resistance, R_t

3.1 Square Footing

$$R_t = \rho_s /2\pi [(1/a) + (2.707/w)] \quad (\Omega) \qquad (7)$$

Where, ρ_s = soil resistivity (Ω.m)
a = footing radius (m)
w = footing spacing (m)

3.2 Single Augured Footing

$$R_t = [\rho_s / (2 \pi L)] [\ln (2 L/a)] \quad (\Omega) \qquad (8)$$

Where, ρ_s = soil resistivity (Ω.m)
L = footing length (m)
a = footing radius (m)

3.3 Four Augured Footing

$$R_t = 0.25 (R_s + R_{m1} + R_{m2} + R_{m3}) \qquad (9)$$

Where, R_s = footing self resistance from equation (8)
R_{m1}, R_{m2}, R_{m3} = mutual resistances to other footings from equation (10)

$$R_m = [\rho_s / (2 \pi L)] [\ln \{(L/x) + \mathrm{SQRT}(1+(L^2/x^2))\}] \quad (\Omega) \qquad (10)$$

Where, L = footing length (m)
x = distance to the other footings in turn (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = \sqrt{Z_s \, l \, R_t} \quad (\Omega) \qquad (11)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
l = span length (km)
R_t = tower footing resistance (Ω)

5. Shielding Factor, S

$$S = 1 - (Z_m / Z_s) \qquad (12)$$

Where, Z_m = conductor earth return mutual impedance (Ω/km)
Z_s = conductor earth return self impedance (Ω/km)

APPENDIX B

ASSUMPTIONS IN ESTIMATING GROUND POTENTIAL RISE FOR AN LV FAULT

The grounding system performance in the event of a 44-kV line-to-ground fault on a pole outside the station was estimated based on the following assumptions.

a) The faulted pole at a distance of 500 m from the station centre.

b) The poles carry 8-kV secondary distribution circuits with under-built neutrals of size 85 mm^2 (AWG 3/0) ACSR and the fault occurs between a 44-kV line and the neutral.

c) Secondary distribution taps to farmers at 500 m spacings.

d) A ground resistance of 5 Ω at each farm house.

e) Ground rod resistance at distribution taps along poles neglected compared to the neutral impedance.

f) The 44-kV phase conductors are 171 mm^2 (336.4 kcmil) ACSR.

g) Source impedance based on a 44-kV station fault current of 6.8 kA as provided by System Planning Department.